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Sustainable water allocation strategies under various climate scenarios: A case study in China

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ABSTRACT

Increasing water demand aggravates water scarcity in water-scarce regions (e.g., India, Pakistan, and China), where uneven precipitation increases the risk of maintaining sustainable eco-economic development. Ignoring precipitation's effects leads to misguided policy recommendations that either deplete or underuse basin water resources. Therefore, this paper highlights the concept of uneven precipitation and uncertain stream inflow based on scenario analysis. Within a river basin, the regional authority and subarea managers both have water allocation and reallocation privileges. Motivated by sustainable development of water resource management systems, we argue that regional authorities should focus on alleviating the contradiction between supply and demand, and then seeking an optimum allocation strategy to ensure societal and economic benefits for its subareas, from which the subareas can provide reasonable reaction strategies. Authorities dominate water transactions between subareas involved in water rights distribution. This paper proposes a multi-objective multi-stage Stackelberg-Nash-Cournot (m^2SNC) game model to cope with conflicts between regional authorities and subarea managers concerning multiple activities. An interactive-dynamic-programming-based genetic algorithm (IDP-GA) is designed to simulate the policies needed for the optimum allocation of water resources under various climate scenarios. The significant stress caused by unsustainable water resource allocation has been a perplexing problem for Sancha Lake, an important area in the southeast basin of the Dujiangyan Irrigation System in China. To identify the tradeoffs among stakeholders, we apply the proposed model to this basin. To gain further insight into climate change and water usage sustainability, we simulate the varying spatial and seasonal distribution of stream inflow based on historical climate data and propose different water management strategies for normal, slight drought, moderate drought, and serious drought conditions. This creates an emergency response co-operative mechanism based on different climate scenarios for developing countries that need to cope with water deficiency and uncertain situations.

1. Introduction

Unreasonable water policies have exacerbated the problem of water resources deficiency, which is a major obstacle to sustainable water resources management (Chen et al., 2013). Around the globe, diverse water governances have devoted themselves to implementing measures to ensure healthy and sustainable water resource usage over long periods of time (Özerol et al., 2018), in order to adapt to rapid increases in water demand from the municipal, industrial, and agricultural sectors (Fu et al., 2018; Wang et al., 2012). In this paper, we develop a balance between water supply and demand for the present and future of a river basin.

Water resources allocation optimization has become more complex than ever before, especially when it comes to water resources systems designed for multiple activities, such as initial water rights allocation, water withdrawal, and subsequent water rights transactions (Wang et al., 2008; Bekchanov et al., 2015). In China, the strategic interaction within a water resources system is that the regional authority assigns the original water rights. After initial water rights are allocated, the rights become personal property that can be traded in water markets for profit or withdrawn for use. A water market refers to the water rights trading mechanisms that have become an important economic tool in achieving water resource planning optimization, because of improved water use and allocation efficiency after water transactions (Easter and Hearne, 1995). In many developing countries such as China, the water market is not considered a complete market, but rather a quasi-market,

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because it cannot be separated from the regional authority's macro control. It is vital to take into account the different actors and networks that help formulate and implement water policies (Araral and Yu, 2013; Araral and Wu, 2016). Combined with the bi-level structure of water resources systems, regional water resource planning under market mechanisms is a type of Stackelberg-Nash game.

Conflicts exist between regional authorities and subarea managers over water allocation. The regional authority, in the leading position, has the fundamental goal to match the water demand of the socio-economic system to the supply of the water system through administrative control and management (water laws, regulations, and infrastructure), without compromising the ecosystem's sustainability in each subarea (Dong et al., 2013). Subarea managers, as followers, focus on economic utilization. Increasingly in the last decade, regions where demand outstripped water resource availability have suffered from severe chronic shortages, particularly when faced with rapid population increases and rapid economic development. This competitiveness worsens agricultural water shortages and other serious problems (e.g., agricultural sustainability concerns), which most often arise because of poorly planned water-management systems in which limited water resources are available to multiple competing users (Xu and Zhou, 2011). This has intensified the controversial and conflict-laden water allocation issues among multiple competing interests (e.g., municipal, industrial, and agricultural) (Xie et al., 2015).

We treat the conflicts between regional authorities and subarea managers as a form of "leader–follower" behavior (Stackelberg, 1934), where the conflicts can arrive at a Stackelberg-Nash equilibrium at the upper decision-making level (Nash, 1951). Considering that subarea managers are independent decision makers, and that they have incentives to maximize their own benefits, a Cournot-Nash equilibrium should be achieved at the lower decision-making level (Cournot, 1838). In this paper, we propose an optimal strategy for river basin water allocation by pursuing Stackelberg-Nash and Cournot-Nash equilibria, which can be called the Stackelberg-Nash-Cournot (SNC) equilibrium (Sherali et al., 1983). The SNC equilibrium reflects the trade-offs in the bi-level decision conflicts between regional authorities and subarea managers.

Many prior studies have focused on regional water resource planning problems, and many models and algorithms have been developed (Ahmad et al., 2018; Faqiry and Das, 2017; Fu et al., 2018). However, regional water resource planning is not only a bi-level optimization problem, but also a dynamic optimization process, as the decision makers in both the upper and lower levels need to make decisions over multiple stages. Li et al. considered ecological water demand and optimized water resources allocation through a multi-stage stochastic programming method (Li et al., 2018). Chen proved that annual inflow was nonstationary, and provided a foundation for water managers who manage water resources under nonstationary and stochastic conditions (Chen et al., 2018). Tsai et al. proposed an intelligent water allocation system (IWAS) to reduce the water pressure in multiple sectors and enhance the resilience of the water allocation system in urban areas during droughts, by using system dynamics (Tsai et al., 2019). Zhuang et al. uncovered the complexities in water allocation problems where interactions and dynamic relationships exist in a multi-stage context (Zhuang et al., 2018). To our best knowledge, since water resources distribution is spatially and seasonally uneven, water allocation should be divided into multiple stages (Piao et al., 2010; Gleick, 2002; Gleick, 2003; Vörösmarty et al., 2000; Wang, 2012). Most importantly, it is appropriate to conceptualize water allocation problems in a bi-level multi-stage framework that fully considers the interests, not only of the regional authority, but also the subarea managers. Unfortunately, there are only a few studies that have looked at water management in terms of the combination of bi-level optimization and multi-stage decision-making. Therefore, in this paper, we combine bi-level optimization with dynamic optimization, which largely conforms to realistic practices. It is worth noting that, within a river basin, the upper- and lower-level decision makers all have multiple objectives in order to optimize their satisfaction, economic benefits, and water use efficiency.

When modeling, many parameters possess imprecise numerical quantities due to their inherent complexity and stochastic uncertainty. It is worth noting that climate change and its impact on water resources is a major challenge that China and the rest of the world will have to cope with in the twenty-first century (Mekanik et al., 2016; Piao et al., 2010; Grafton et al., 2013). Uncertainties in future changes in precipitation prevent analysts from making firm statements about how river flows will respond to climate change. This has led to uncertain water supplies in different river basins, which increased the stress on regional authorities and subarea managers. In this case, we applied scenario-based analysis to consider the influence of various stream inflows. As we know, scenarios can address a broad range of "what if" questions such as, what if a minor drought occurs? What if a severe drought occurs? Therefore, we examined four stream flow patterns and a detailed regional water allocation scenario analysis using the proposed model.

This paper aspires to contribute to the discussion about regional water resource planning by constructing a bi-level multi-stage decision making model with multiple lower-level decision makers, accompanied by a scenario-based analysis, and by obtaining solutions that optimize both total benefits to society and economic benefits for each subarea (i.e., to satisfy the upper and lower objectives). The bi-level multi-stage decision making method proposed in this paper creates a greater motivation to save water, and alleviates the contradiction between supply and demand by introducing a water rights concept and a water market in more complex circumstances that include multiple decision makers on the lower level. There is a set of scenarios that describes several possible stream flow patterns for the Sancha Lake area water resource allocation problem, which is more suitable for describing the uncertain environment encountered in real-life regional water resource planning. When actual representations are available, the regional water resource planning problem can be solved more realistically. This paper develops an IDP-GA to solve the model, and presents the results and analysis for the Sancha Lake area to demonstrate the practicality and efficiency of the optimization method.

The remainder of this paper is organized as follows. Section 2 presents the key issues in defining the water resource allocation problem in the Min River Basin and details the modelling approach for the establishment of a bi-level multiple objective multi-stage decision making model to describe the water resource allocation problem. Then it develops an IDP-GA for the optimum allocation of water resources under various climate scenarios. Section 3 presents the results and describes an early-warning system. Section 4 summaries the different water allocation strategies under varying stream inflow levels and discusses some policy implications. Finally, Section 5 gives some concluding remarks and points to future research possibilities.

2. Material and methods

2.1. Motivation of developmental issues in study area

Sancha Lake Reservoir (see the right side of Fig. 1), the farthest and last important node in the Dujiangyan irrigation system, is located in the eastern foot of Longquan near Chengdu, which is 40 km to the northwest and has 27 square kilometers of open lakes. Based on its geographical location, the "Tianfu New" plan divides the Sancha Lake area into three subareas: the Sancha area, the Xinmin area, and the Dongjiageng area. The "Tianfu New" plan provides a broad context requiring a water supply management plan to be set up under the government's water strategy, "The future water resources allocation and planning for the Dujiangyan Irrigation System area of Min River basin in the 13th Five-Year Plan (2015–2020)." This strategy acknowledges the pressure on future water resources from population growth (and housing) and climate change.

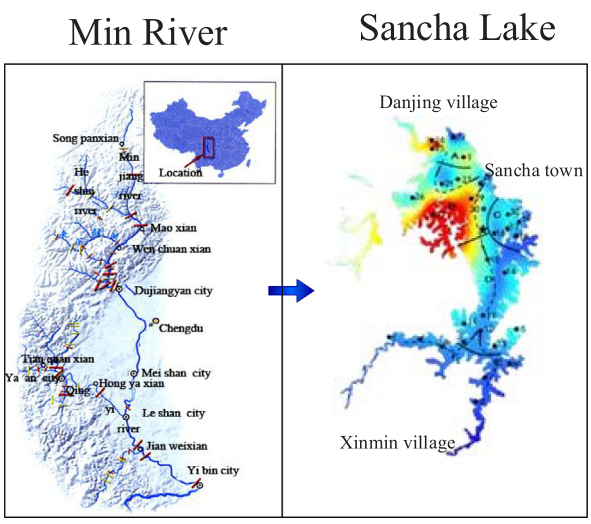

Fig. 1. Sancha Lake area location.

Traditional water resource allocation plans cannot deal with water demand conflicts in different subareas and thus, many problems related to equity, efficiency, and sustainability have arisen. Considering the developmental issues above, the general aim of this study is to establish an integrated water resource management plan for the Sancha Lake area in order to achieve both economic and ecological sustainability. Here, we focus on the idea of sustainable water resources allocation in a river basin and analyze the characteristics of the Sancha Lake area in the Dujiangyan Longquanshan irrigation district in the Min River Basin of China.

2.2. Conceptual framework: bi-level multistage water resource allocation

Before formulating a mathematical model, we first constructed a conceptual framework (Xu and Zeng, 2013). The Sancha Lake area committee is the upper-level decision maker. At each stage, the total available water from the Sancha Lake area is considered a state variable. The decision maker on the upper level allocates water rights to different subareas and stores the upstream water in the reservoir. The lower-level decision maker is the subarea water manager. Each subarea has a reservoir to store its water, and it can trade water in the water market under government regulation. The water input for each subarea includes the water obtained from the regional authority, the water bought in the water market under government control, and the water stored in the subarea reservoir. Water availability is a key factor in local area development, and increased demand for water by the agricultural, industrial, and municipal sectors increases pressure for equitable allocation. At each stage, each subarea water manager allocates water to industrial, municipal, and agricultural water users. Municipal water use includes residential use, drinking water, tourist use, and municipal services. Industrial water supplies the chemical, food, papermaking, mechatronics, and construction industries. Agricultural water use includes water for irrigation, livestock, fisheries, and forests.

It is worth noting that the water resource allocation decision making process is considered a multistage decision making process. The entire decision making process is divided into several stages with decision making required in each stage. In a multistage decision making process, the decisions made in a previous stage influence the state of the next stage (Xu et al., 2013c; Xu and Zeng, 2014). As a result the decision maker needs to not only consider the situation in the current stage, but also have a full understanding of the influence of the current state on the next stage to optimize decisions over the entire decision-making process. For the Sancha Lake area water resource allocation, the length of each stage is one month. The multistage decision making state transit mechanism for the upper and lower levels is explained in the following.

2.3. Model proposition

A bi-level multiple objective multistage programming model is constructed. The entire model is composed of the lower and upper level objectives, constraints, and state transit equations.

2.3.1. Fundamental assumptions

Before constructing the model, the following assumptions are involved:

(1) All available water for distribution is provided by a single river basin.
(2) The Sancha Lake Area Committee in the upper level and each subarea manager on the lower level make rational decisions cooperatively to avoid an unsatisfactory situation.
(3) Each decision maker on the upper and lower levels fully understands the objective functions and the inherent constraints. Each subarea manager on the lower level behaves rationally.
(4) When the water withdrawal of a subarea is more than its assigned initial water right and the stored water, it needs to buy water from the water market under government control; conversely, it can sell extra water on the water market under government control.
(5) The total stream flow volume in the river basin is considered a fuzzy random variable, with attributes statistically determined using historical data and professional experience, which has to be further changed to a deterministic variable.

2.3.2. Notation

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(1) Subscripts:

i = index of subarea in the river basin, where $i = 1, 2, \cdots, n$;
k = index of water user in the subarea, where $k = 1, 2, \cdots, m$;
t = index of stages for the regional water resources planning and management, where $t = 1, 2, \cdots, T$;

(2) Certain Parameters:

$\xi(t)$ = total volume of upstream flow in the river basin in stage t;
A_0, A_{T+1} = initial and terminal available water in the river basin at the beginning and at the end of the decision making stages;
$b_{ik}(t)$ = benefit parameter for water user k in subarea i in stage t per unit of water allocated (RMB/m^3);
$I_{ik}^{\min}(t)$, $I_{ik}^{\max}(t)$ = minimal and maximal satisfaction limitations of the water withdrawal of user k in subarea i in stage t;
$L_i^{\min}(t)$, $L_i^{\max}(t)$ = minimal and maximal satisfaction limitations of the allocated water rights of subarea i in stage t;
s_i^0, s_i^{T+1} = initial and terminal stored water in subarea i at the beginning and end of the decision making stages;
Tax_k = tax charge of per unit of water resources from user k;
κ, σ = water transaction price function coefficients;
$S_i^{\max}$ = maximal volume of stored water in subarea i;

(3) State Variables:

$A(t)$ = available water in the river basin in stage t;

(4) Functions:

$p(\text{BSW}_i^+(t))$ = the water rights transaction price function in water market in stage t;
$g_{il}(x_i(t))$ = upper level objective function of social satisfaction degree of each subarea;
$W(x_i(t))$ = upper level objective function of water availability level;
$Q(y_{ik}(t))$ = upper level objective function of total economic benefit;
$f_{ikt}(y_{ik}(t))$ = lower level objective function of satisfaction degree of each stage for each water user for each subarea;
$U_i(y_{ik}(t), \text{BSW}_i(t))$ = lower level objective function of economic utility for each subarea;

(6) Decision variable

$x_i(t)$ = initial water rights of subarea i in stage t, determined by the upper level decision maker;

$y_{ik}(t)$ = water withdrawal of user k in subarea i in stage t, determined by the lower level decision maker;

$\mathrm{BSW}_i(t)$ = to buy (i.e., $\mathrm{BSW}_i^+(t)$) or sell (i.e., $\mathrm{BSW}_i^-(t)$) water of subarea i in stage t, determined by the lower level decision maker;

$s_i(t)$ = stored water of subarea i in stage t, determined by the lower level decision maker;

2.3.3. Lower level decision making process

To meet the municipal, industrial, and agricultural water demands, the lower level decision maker (three subarea managers) seek adequate water to maximize their satisfaction degree and economic benefit in accordance with the Sancha Lake Area Committee water rights allocation decisions.

Objective 1: maximize the minimal sectoral satisfaction degree

At the lower level, each subarea manager distributes water to industrial water users, municipal water users, and agricultural water users, respectively. First, a satisfaction degree function of each water user is defined below:

$$f_{ikt}(y_{ik}(t)) = \begin{cases} 0, & y_{ik}(t) \leqslant I_{ik}^{\min}(t), \\ \frac{y_{ik}(t) - I_{ik}^{\min}(t)}{I_{ik}^{\max}(t) - I_{ik}^{\min}(t)}, & I_{ik}^{\min}(t) < y_{ik}(t) < I_{ik}^{\max}(t), \\ 1, & y_{ik}(t) \geqslant I_{ik}^{\max}(t). \end{cases}$$

The satisfaction degree functions assume that for each sector in each stage, there is a basic (minimal) water use volume (denoted by $I_{ik}^{\min}(t)$) as well as a water use maximal volume (denoted by $I_{ik}^{\max}(t)$). That is, if the water withdrawal volume is reduced to less than $I_{ik}^{\min}(t)$, the satisfaction degree reduces to zero (0); thus if the water withdrawal volume increases to more than $I_{ik}^{\max}(t)$, the satisfaction degree cannot increase to more than one (1). Each subarea manager (i.e., the Sancha area, the Xinmin area, and the Dongjiageng area) wants to maximize the minimal satisfaction degree in each stage for each water user at each subarea, thus:

$$\max_{\mathbf{y}} \min_{k,t} \{f_{ikt}(y_{ik}(t))\}, \quad \text{for } k = 1, 2, 3, \text{ and} t = 1, 2, \cdots, T. \tag{1}$$

Objective 2: Maximize the economic utility To measure the lower level subarea economic performance, the economic utility function is employed. The subarea economic benefit is $\sum_{k=1}^{m}\sum_{t=1}^{T} b_{ik}(t)\cdot y_{ik}(t)$, and the subarea economic investment is $\sum_{k=1}^{m}\sum_{t=1}^{T}[\mathrm{Tax}_k\cdot y_{ik}(t) + p(\mathrm{BSW}_i^+(t))\cdot \mathrm{BSW}_i^+(t)]$, thus the economic utility function can be expressed as:

$$U_i(y_{ik}(t), \mathrm{BSW}_i(t)) = \sum_{k=1}^{m}\sum_{t=1}^{T} b_{ik}(t)\cdot y_{ik}(t) - \sum_{k=1}^{m}\sum_{t=1}^{T}[\mathrm{Tax}_k\cdot y_{ik}(t) + p(\mathrm{BSW}_i^+(t))\cdot \mathrm{BSW}_i(t)]. \tag{2}$$

The water manager also wants to maximize each subarea's economic utility (i.e., Sancha area, Xinmin area, and Dongjiageng Area) as shown below:

$$\max_{\mathbf{y}} U_i(y_{ik}(t), \mathrm{BSW}_i(t)), \quad \text{for} \quad i = 1, 2, \cdots, n. \tag{3}$$

Although the water market is not a completely competitive market (Coase, 1960) as it is controlled by the government, market prices are still influenced by the relationship between supply and demand within a reasonable range. Namely, the price rises when demand is greater than supply; conversely, the price drops. According to a theoretical analysis of the oligarch competition model (Easter and Hearne, 1995), the water rights transaction price function in a water market under government control can be expressed as:

$$p(\mathrm{BSW}_i^+(t)) = \kappa - \sigma\cdot\sum_{i=1}^{n} \mathrm{BSW}_i^+(t), \tag{4}$$

where $\sum_{i=1}^{n} \mathrm{BSW}_i^+(t)$ represents the total available water for trading in the water market in stage t;$\mathrm{BSW}_i^+(t)$ is the volume of water bought, and $\mathrm{BSW}_i^-(t)$ is the volume of water sold; κ and σ are the positive parameters.

Lower level constraints

State transit of stored water: The state transit equation describes the relationship between the decision and state variables in each stage (Xu et al., 2013c). For the lower-level decision makers, the stored water is considered a state variable. The input water of a subarea includes the current stored water, the allocated water rights from the Sancha Lake Area Committee, and the traded water in the water market under government control. So then the state transit equation for the lower level is:

$$s_i(t+1) = s_i(t) - \sum_{k=1}^{m} y_{ik}(t) + x_i(t) + \mathrm{BSW}_i(t). \tag{5}$$

Initial and terminal conditions of stored water: The initial and terminal conditions describe the stored water level at the beginning and at the end of the whole decision making procedure:

$$s_i(1) = s_i^0, \quad \text{and} \quad s_i(T+1) \geqslant s_i^{T+1}. \tag{6}$$

Constraints on stored water: The volume of the stored water in each subarea has a maximal limitation (i.e, $S_i^{\max}$) and should be nonnegative:

$$0 \leqslant s_i(t) \leqslant S_i^{\max}, \tag{7}$$

wherein zero (0) excludes minimal environmental reservation for livestock and ecological water usage.

Constraints on water withdrawal: There are also nonnegative constraints on the decision variable $y_{ik}(t)$ because the water withdrawal of user k in subarea i in stage t cannot be nonnegative:

$$y_{ik}(t) \geqslant 0. \tag{8}$$

2.3.4. Upper level decision making process

As the upper level decision maker, the Sancha Lake Area Committee considers equity, efficiency, and sustainability among the three subareas when making the water rights allocation decisions. Hence, three objective functions are considered.

Objective 1: maximize the minimal social satisfaction degree

The Sancha Lake Area Committee needs to create a plan to effectively allocate the water supply to the subareas to maximize the minimal social satisfaction degree in each subarea (i.e., Sancha area, Xinmin area, and Dongjiageng area). The social satisfaction degree for each subarea is defined by the function

$$g_{it}(x_i(t)) = \begin{cases} 0, & x_i(t) \leqslant L_i^{\min}(t), \\ \frac{x_i(t) - L_i^{\min}(t)}{L_i^{\max}(t) - L_i^{\min}(t)}, & L_i^{\min}(t) < x_i(t) < L_i^{\max}(t), \\ 1, & x_i(t) \geqslant L_i^{\max}(t). \end{cases} \tag{9}$$

The social satisfaction degree function assumes that for each subarea there is a basic (minimal) volume of water allocated and maximal water use. That is, if the water allocation volume is less than $L_i^{\min}(t)$, the satisfaction degree for that subarea is reduced to zero (0). However, if the water allocation volume increases to be more than $L_i^{\max}(t)$, the satisfaction degree of that subarea cannot increase to more than one (1). As a result, the objective function for the social satisfaction degree is to maximize the minimal social satisfaction degree:

$$\max_{\mathbf{x}} \min_{i,t} \{g_{it}(x_i(t))\}. \tag{10}$$

Objective 2: maximize the water availability

To guarantee water resource allocation efficiency in the upper level, the Sancha Lake Area Committee wants to maximize the water availability level for the whole river basin:

$$\max_{\mathbf{x}} \{W(x_i(t))\}, \tag{11}$$

where the water availability level is defined as:

$$W(x_i(t)) = \frac{\sum_{i=1}^{n}\sum_{t=1}^{T} x_i(t)}{\sum_{t=1}^{T}(A(t)+\xi(t))}.$$

Objective 3: maximize the total economic benefit

The total economic benefit got from user k in subarea i is defined as:

$$Q(y_{ik}(t)) = \sum_{i=1}^{n}\sum_{k=1}^{m}\sum_{t=1}^{T} b_{ik}(t)\cdot y_{ik}(t). \tag{12}$$

Obviously, the goal of the upper level decision maker is to maximize the benefit, namely:

$$\max_{\mathbf{y}}\{Q(y_{ik}(t))\}. \tag{13}$$

Upper level constraints

Constraints on water trading: The water can only be traded among the subareas in the river basin in the water market under government control. When $\mathrm{BSW}_i(t)$ is positive, water is bought, and when $\mathrm{BSW}_i(t)$ is negative, water is sold. The following equations clearly show the volume of water bought and sold in the market:

$$\mathrm{BSW}_i(t) = \mathrm{BSW}_i^{+}(t) - \mathrm{BSW}_i^{-}(t), \quad \text{and} \quad \mathrm{BSW}_i^{+}(t)\times\mathrm{BSW}_i^{-}(t) = 0, \tag{14}$$

where $\mathrm{BSW}_i^{+}(t) \geqslant 0$ is the volume of water bought and $\mathrm{BSW}_i^{-}(t) \geqslant 0$ is the volume of water sold.

For each stage, therefore, the sum of all the bought and sold water should be zero (0):

$$\sum_{i=1}^{n}\{\mathrm{BSW}_i^{+}(t) - \mathrm{BSW}_i^{-}(t)\} = 0. \tag{15}$$

The volume of water sold in each stage for subarea i cannot exceed the allocated water rights:

$$\mathrm{BSW}_i^{-}(t) \leqslant x_i(t). \tag{16}$$

Constraints on water allocation: There are also nonnegative constraints on the decision variable $x_i(t)$. Because the initial water rights for each subarea in each stage cannot be negative:

$$x_i(t) \geqslant 0. \tag{17}$$

The volume of the available water in the Sancha Lake Area has a maximal limitation (i.e, $A^{\max}$) and cannot be negative:

$$0 \leqslant A(t) \leqslant A^{\max}. \tag{18}$$

where zero (0) excludes the minimal environmental reservation for livestock and ecological water usage.

State transit of total available water: For the upper level decision maker, the total available water is considered a state variable. Multistage decision making is actually a discrete dynamic process.

The Sancha Lake area output water is the allocated water rights to the subareas, so the state transit equation for the upper level is as below:

$$A(t+1) = A(t) - \sum_{i=1}^{n} x_i(t) + \xi(t). \tag{19}$$

Initial and terminal conditions for total available water: The initial and terminal conditions describe the available water level at the beginning and at the end of the complete decision making process as shown below:

$$A(1) = A_0, \quad \text{and} \quad A(T+1) \geqslant A_{T+1}. \tag{20}$$

2.4. The global model – m^2SNC model

There is an interactive relationship between the upper- and lower-level decision makers. The regional authority on the upper level (i.e., the leader) makes decisions regarding the initial water rights of the subareas to guarantee equity and efficiency, and the followers, or lower-level decision makers, are the subarea managers who decide on the volume of water withdrawal that maximizes satisfaction and economic benefits. This relationship can be described as a multi-objective multi-stage Stackelberg-Nash-Cournot (m^2SNC) problem. The state transit equations, Eqs. (5) and (19), describe a dynamic decision making process where the available water in the Sancha Lake area and the stored water in the reservoirs in each subarea is regarded as a state variable. The constraints on the decision variables, as well as the initial and terminal conditions, restrict the water resource allocation to within feasible limits. The objective functions for the two-level decision makers, as shown in Eqs. (1), (3), (10), (11), and (13), reflect the multiple goals and conflicts over decisions between the Sancha Lake Area Committee and the subarea water managers. By integrating the state transit equations, constraints, initial and terminal conditions, and objective functions, the m^2SNC model for optimizing the bi-level, multiple objective, multi-stage water resource allocation in the Sancha Lake area can be formulated as:

$$\begin{cases}
\max\limits_{\mathbf{x}}\min\limits_{i,t}\{g_{it}(x_i(t))\}\\
\max\limits_{\mathbf{x}}\{W(x_i(t))\}\\
\max\limits_{\mathbf{y}}\{Q(y_{ik}(t))\}\\
\begin{cases}
\sum_{i=1}^{n}\{\mathrm{BSW}_i^{+}(t) - \mathrm{BSW}_i^{-}(t)\} = 0,\\
\mathrm{BSW}_i^{-}(t) \leqslant x_i(t),\\
A(t+1) = A(t) - \sum_{i=1}^{n} x_i(t) + \xi(t),\\
A(1) = A_0,\\
A(T+1) \geqslant A_{T+1},\\
0 \leqslant A(t) \leqslant A^{\max},\\
x_i(t) \geqslant 0,\\
\max\limits_{\mathbf{y}}\min\limits_{k,t}\{f_{ikt}(y_{ik}(t))\}, \quad i = 1, 2, \cdots, n\\
\max\limits_{\mathbf{y}}\{U_i(y_{ik}(t), \mathrm{BSW}_i(t))\}, \quad i = 1, 2, \cdots, n\\
s.t.\begin{cases}
s_i(t+1) = s_i(t) - \sum_{k=1}^{m} y_{ik}(t) + x_i(t) + \mathrm{BSW}_i(t),\\
s_i(1) = s_i^0,\\
s_i(T+1) \geqslant s_i^{T+1},\\
\mathrm{BSW}_i^{+}(t)\times\mathrm{BSW}_i^{-}(t) = 0,\\
\mathrm{BSW}_i^{+}(t) \geqslant 0, \quad \mathrm{BSW}_i^{-} \geqslant 0,\\
0 \leqslant s_i(t) \leqslant S_i^{\max},\\
y_{ik}(t) \geqslant 0.
\end{cases}
\end{cases}
\end{cases} \tag{21}$$

2.5. IDP-GA solution procedure

The proposed model (21) provides the Sancha Lake Area Committee with an efficient tool to cope with the realistic stresses resulting from unreasonable water resource allocation. However, the inherently complicated environment, with a changing climate, increasing population size, and growing economic development, usually requires the proposed model to dynamically fit various scenarios. Hence, a procedure for policy simulation based on an IDP-GA is designed to simulate the optimal strategies for the water resource allocation and further assist each level of authority to develop efficient policies.

Using the IDP-GA under various climate change scenarios to investigate the impact of climate change on the Sancha Lake area water resource allocation, some scheduling principles for water resource

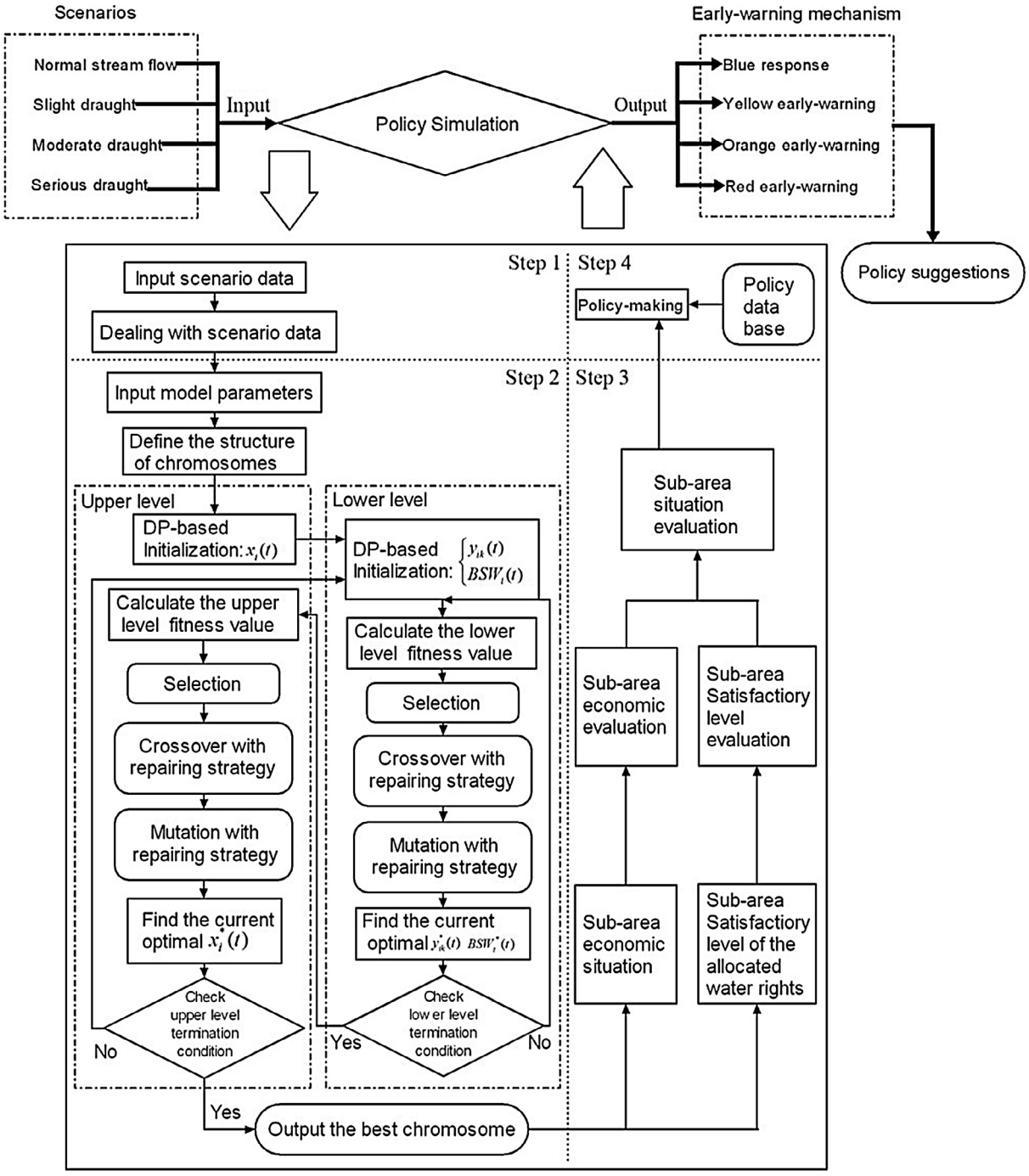


Fig. 2. Overall procedure of the IDP-based GA.

allocation and a framework for the policy simulation are presented. This simulation is similar to, but not the same as the computable general equilibrium (CGE) model (Johansen and Zabel, 1962), which originated from Leontief's input-output system (Leontief, 1936), an efficient tool to simulate how an economy might react to changes in policy, technology or other external factors by developing a series of equations describing model variables.

The framework for the overall IDP-based GA procedure the bi-level multiple objective regional water resource planning problem is shown in Fig. 2. And the pseudo-code is shown in Appendix II. This procedure integrates interactive dynamic programming into a genetic algorithm (IDP-GA) to satisfy the four situations (bi-level structure, multiple objectives, multiple stages and twofold uncertainty) proposed in the model for the Sancha Lake area water resource allocation.

3. Results

The proposed optimization method has been developed to deal with development issues in the Sancha Lake area irrigation district in the Min River Basin.

3.1. Data collection and parameters determination

Data collection was conducted by studying the historical data archive and suggestions from experts, and was then dealt with using policy and parameter framework principles. In the Sancha Lake area

Table 1
Parameters for available water and water transaction price.

Item	$A_0(10^3\ m^3)$	$A_{12}(10^3\ m^3)$	$A^{max}(10^3\ m^3)$	κ(RMB/$10^3\ m^3$)	σ(RMB/($10^3 m^3$))
Parameter	20,000	20,000	30,000	6×10^3	1.2×10^3

Table 2
Parameters for the water withdrawal minimal satisfaction limitation ($10^3\ m^3$).

Month	*SC*			*XM*			*DJG*		
	$k = 1$	$k = 2$	$k = 3$	$k = 1$	$k = 2$	$k = 3$	$k = 1$	$k = 2$	$k = 3$
Jan	90.35	432.29	43.00	108.12	384.59	51.46	97.75	176.89	46.53
Feb	90.35	1175.34	43.00	108.12	1045.65	51.46	97.75	480.94	46.53
Mar	90.35	377.16	43.00	108.12	335.54	51.46	97.75	154.33	46.53
Apr	90.35	743.05	43.00	108.12	661.05	51.46	97.75	304.05	46.53
May	90.35	3628.77	43.00	108.12	3228.36	51.46	97.75	1484.88	46.53
Jun	90.35	2354.44	43.00	108.12	2094.64	51.46	97.75	963.43	46.53
Jul	90.35	974.86	43.00	108.12	867.29	51.46	97.75	398.91	46.53
Aug	90.35	1647.73	43.00	108.12	1465.91	51.46	97.75	674.24	46.53
Sep	90.35	315.76	43.00	108.12	280.92	51.46	97.75	129.21	46.53
Oct	90.35	125.30	43.00	108.12	111.48	51.46	97.75	51.27	46.53
Nov	90.35	195.47	43.00	108.12	173.90	51.46	97.75	79.99	46.53
Dec	90.35	560.10	43.00	108.12	498.30	51.46	97.75	229.19	46.53

irrigation district, the three subareas (i.e., $i = 1, 2, 3$, representing the Sancha area, the Xinmin area, and the Dongjiageng area, respectively) mainly supply water to three types of water users ($k = 1, 2, 3$, with $k = 1$ for municipal users, $k = 2$ for agricultural users, and $k = 3$ for industrial users).

Detailed information for the Sancha Lake area regional authority on the upper level and the subarea managers on the lower level is shown in Tables 1–8. The stream inflow in the t-th month is shown in Table 4. The minimal and maximal satisfaction limitation parameters for the allocated water rights, and the stored water parameters in the subareas have been shown in Tables 5 and 6.

The initial stored quantity at the beginning of January and the final stored quantity at the end of December for the Sancha area, the Xinmin area, and the Dongjiageng area are listed, below:

$$s_1(1) = 5000, \quad s_1(13) \geqslant 5000, \quad s_2(13) = 5000, \quad s_2(13) \geqslant 5000, \quad s_3(13) = 4000, \quad s_3(13) \geqslant 4000.$$

The IDP-GA-based simulation parameters are set from the results of the preliminary experiments that were conducted to observe the behavior of the algorithm at different parameter settings. By comparing several sets of parameters, including population size (i.e., $N = 25$), iteration number (i.e., $I = 500$), crossover probability (i.e., $p_c = 0.2$), and mutation probability (i.e., $p_m = 0.4$), the most reasonable parameters are chosen to trade off between the evaluation time and population size (Kim and Ellis, 2008). The program was run 10 times on a Core *i*5, 3.20 GHz clock pulse with 4 GB memory.

3.2. Allocation solution with a normal stream flow

If rainfall is relatively adequate all year round, then the upstream is able to provide the downstream with enough water in most months. Then the upper decision maker, namely the Sancha Lake Committee, considers the lower decision maker's requirements under some essential constraints and their optimum reaction duties. Table 9 shows the allocation strategy for the subareas. Fig. 3 exhibits the degree of satisfaction and economic utility of the three subareas. More than 80% of the months of degree of satisfaction are greater than the reference level of 0.903 in both the Sancha and Xinmin Areas. Similarly, more than 80% of the months of the degree of satisfaction are in the reference interval (0.732, 0.903) in the Dongjiageng Area.

Based on the results, we suggest that the upper decision maker, namely the Sancha Lake Committee, would only need to consider the equity and efficiency of the water resources allocation in order to ensure that the whole basins development is balanced. The Dongjiageng Area would need to formulate efficient measures to cope with a lack of water in some periods; for example, by ensuring that there is a full reservoir in advance or instructing locals to use less water.

Table 3
Parameters for the water withdrawal maximal satisfaction limitation (baseline scenario) ($10^3\ m^3$).

Month	*SC*			*XM*			*DJG*		
	$k = 1$	$k = 2$	$k = 3$	$k = 1$	$k = 2$	$k = 3$	$k = 1$	$k = 2$	$k = 3$
Jan	120.46	576.39	57.34	144.16	512.79	68.62	130.34	235.86	62.04
Feb	120.46	1567.12	57.34	144.16	1394.20	68.62	130.34	641.26	62.04
Mar	120.46	502.88	57.34	144.16	447.39	68.62	130.34	205.78	62.04
Apr	120.46	990.73	57.34	144.16	881.41	68.62	130.34	405.40	62.04
May	120.46	4838.36	57.34	144.16	4304.47	68.62	130.34	1979.84	62.04
Jun	120.46	3139.26	57.34	144.16	2792.85	68.62	130.34	1284.57	62.04
Jul	120.46	1299.81	57.34	144.16	1156.38	68.62	130.34	531.88	62.04
Aug	120.46	2196.98	57.34	144.16	1954.55	68.62	130.34	898.99	62.04
Sep	120.46	421.02	57.34	144.16	374.56	68.62	130.34	172.28	62.04
Oct	120.46	167.07	57.34	144.16	148.64	68.62	130.34	68.36	62.04
Nov	120.46	260.63	57.34	144.16	231.87	68.62	130.34	106.65	62.04
Dec	120.46	746.81	57.34	144.16	664.40	68.62	130.34	305.59	62.04

Table 4
Parameters for the Sancha Lake monthly normal stream inflow (10^3 m^3).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$\xi(t)$	919.41	510.78	408.63	1225.88	2814.20	6898.66	9126.92	9499.45	6898.66	3048.71	2043.14	1021.57

Table 5
Minimal and maximal satisfaction limitation parameters for the allocated water rights (10^3 m^3).

Month	L_{min}			L_{max}		
	SC	*XM*	*DJG*	*SC*	*XM*	*DJG*
Jan	565.65	544.18	321.17	754.19	725.57	428.23
Feb	1308.69	1205.23	625.23	1744.92	1606.98	833.63
Mar	510.51	495.13	298.61	680.68	660.17	398.15
Apr	876.40	820.64	448.33	1168.53	1094.19	597.78
May	3762.12	3387.94	1629.16	5016.16	4517.25	2172.21
Jun	2487.79	2254.22	1107.71	3317.06	3005.63	1476.94
Jul	1108.21	1026.87	543.19	1477.61	1369.16	724.25
Aug	1781.08	1625.50	818.53	2374.78	2167.33	1091.37
Sep	449.11	440.50	273.49	598.82	587.34	364.65
Oct	258.65	271.06	195.55	344.87	361.41	260.74
Nov	328.82	333.49	224.27	438.43	444.65	299.02
Dec	693.45	657.88	373.47	924.61	877.18	497.96

Table 6
Stored water parameters in the subareas (10^3 m^3).

Parameter	*SC*	*XM*	*DJG*
s_i^0	5000	5000	4000
s_i^{12}	5000	5000	4000
s_i^{max}	8000	8000	5000

Table 7
Tax charge parameters (RMB/10^3 m^3).

Parameter	$k = 1$	$k = 2$	$k = 3$
Tax_k	3400	11,500	12,800

3.3. Early warning mechanism

As a consequence of the increased frequency of droughts and societal vulnerability to extended periods of water deficiency, the economic, social, and environmental impact of droughts has increased significantly worldwide. Traditionally, the response to drought throughout the world has been through a reactive, risk management approach. This approach to drought management responds to a drought once it occurs, in an attempt to improve and accelerate the recovery process.

Before that, the subarea needs to propose reasonable reference levels that activate different early warning mechanisms. The reference level is calculated according to the following principles: first, put the normal annual stream inflow of 44.41 million m^3 into the proposed model, then obtain the reference satisfaction interval (0.903, 1), which is considered the reference interval for normal status (Blue response mechanism, BRM). Second, given a stream flow of (42.61, 44.41) million m^3 into the proposed model, one obtains the reference satisfaction interval (0.732, 0.903), which is considered the slight drought reference interval (Yellow early warning mechanism, YEWM). Third, given a stream flow of (39.97, 42.61) million m^3 into the proposed model, one obtains the reference satisfaction interval (0.497, 0.732), which is considered the moderate drought reference interval (Orange early warning mechanism, OEWM). Fourth, the satisfaction interval (0, 0.497) is considered to be the serious drought reference interval (Red early warning mechanism, REWM). Finally, if 80% of the subarea degrees of satisfaction fall into the interval, a warning graphic, as shown in Fig. 4 with different colors, is created to assist decision makers in responding accurately. As shown in Fig. 5, both the Sancha and the Xinmin Areas are in the BRM; however, in the Dongjiageng Area, the YEWM would be activated. The reason the Dongjiageng Area has a different response mechanism than the Sancha and Xinmin Areas is due to their different industrialization levels. As is often the case, agricultural and municipal water use took place prior to industrialized use of the water. The Dongjiageng Area is the most industrialized region of the three subareas, so the Sancha Lake Committee satisfies the agricultural region (namely the Sancha Area) and the municipal region (namely the Xinmin Area) first when there is a slight lack of water. It should also be noted that there are usually no large differences in satisfaction between the various subareas, because of sufficient rainfall every month. If a subarea encounters a shortage in certain months, the committee transfers the water rights from another subarea through economic compensation.

4. Discussion

A long-term view of the analysis of the sustainable development of water needs to account for fundamental uncertainties resulting from both a limited understanding of the situation and natural stochastic changes. The following section focuses on scenario analysis under changing climate conditions by qualifying stream flow sources. These scenarios represent important factors and processes which have an important role in determining water resource dynamics in a changing climate.

4.1. Climate scenarios determination

Drought is a multidimensional natural hazard that occurs because of natural climate variability, and it is a recurring phenomenon in many areas of the world, but its features vary from region to region. There are three main drought definitions: meteorological, hydrological, and agricultural (Wilhite and Glantz, 1985). We have used the hydrological definition to distinguish the climate scenarios in the Sancha Lake area's archive of historical weather, climate data, and station history information.

From the quality-controlled data for the daily, monthly, seasonal, and yearly temperature, precipitation, wind measurements, radar data, and Dujiangyan Irrigation System drainage functions, we simulated

Table 8
Parameters for benefits (RMB/m^3).

Benefit parameter	*SC*			*XM*			*DJG*		
	$k = 1$	$k = 2$	$k = 3$	$k = 1$	$k = 2$	$k = 3$	$k = 1$	$k = 2$	$k = 3$
$b_{ik}(t)(t = 1, 2, \cdots, 12)$	23,500	55,500	71,400	24,300	58,200	67,800	25,800	57,300	68,200

Table 9
Subarea allocation strategies with the normal inflow level (m^3).

Month	SC			XM			DJG		
	$k = 1$	$k = 2$	$k = 3$	$k = 1$	$k = 2$	$k = 3$	$k = 1$	$k = 2$	$k = 3$
Jan	117.45	562.10	56.29	140.87	499.47	67.24	127.64	229.66	60.83
Feb	117.40	1530.04	56.35	140.56	1359.67	66.96	127.42	627.40	60.68
Mar	117.45	491.69	56.34	140.84	436.56	67.14	127.03	200.34	60.75
Apr	117.64	966.20	56.09	140.98	862.34	66.89	127.09	394.78	60.59
May	117.53	4730.92	56.27	141.04	4193.83	66.80	127.72	1934.67	60.58
Jun	118.08	3072.10	55.93	140.74	2733.32	67.17	126.88	1251.17	60.76
Jul	117.63	1267.23	56.31	140.71	1126.40	67.04	127.33	520.92	60.42
Aug	117.41	2140.19	55.83	141.38	1911.90	67.03	127.02	880.48	60.44
Sep	118.06	410.70	56.00	140.35	365.94	67.25	127.81	168.61	60.46
Oct	118.13	163.00	55.84	141.27	145.53	67.10	127.55	66.61	60.56
Nov	117.64	254.49	55.87	141.30	226.92	67.10	127.34	104.33	60.77
Dec	117.34	729.69	56.40	141.17	651.14	67.23	127.31	298.61	60.75

four climate scenarios for the Sancha Lake area. (1) Normal climate, when the stream flow is greater than 44.41 million m^3 per year; (2) Slight drought, when the stream flow is around 42.61~44.41 million m^3 per year; (3) Moderate drought, when the stream flow is 39.97~42.61 million m^3 per year; and (4) Severe drought, when the stream flow is less than 39.97 million m^3 per year.

4.1.1. Scenario 1 – slight drought (S1)

Drought has been an issue since the beginning of recorded history. The Sancha Lake Area Committee usually considers there to be a slight drought if the annual stream flow falls into the interval of (42.61, 44.41) million m^3. As an input parameter, it is usually considered to be a fuzzy random number. A slight drought results in a slight reduction in the water resource allocation to the downstream subareas, leading to a decrease in both subarea economic utility and degrees of satisfaction (Table 10). From Fig. 6, the Xinmin Area issues an OEWM, and the Sancha and Dongjiageng Areas issue a YEWM. This means that in 80% of the months, the degree of satisfaction of the Sancha and Dongjiageng Areas falls into the reference interval (0.732, 0.903), and in more than 80% of the months, the degree of satisfaction in the Dongjiageng Area is in the reference interval (0.497, 0.732).

In this scenario, efficient policies need to be developed. The Sancha Lake Area Committee needs to design a reasonable coordination mechanism to improve water resource transactions. For example, financial subsidies could be paid to the subareas at a minimum satisfaction level, or non-affected areas could be encouraged to transfer some water rights to the OEWM subarea. The subarea suffering from the slight drought would need to expand their approach to water withdrawal, such as using ground water. Above all, the authority should efficiently allocate water resources, and the subarea should use the water efficiently.

4.1.2. Scenario 2 – moderate drought (S2)

The Sancha Lake Area is an irrigation region where agriculture

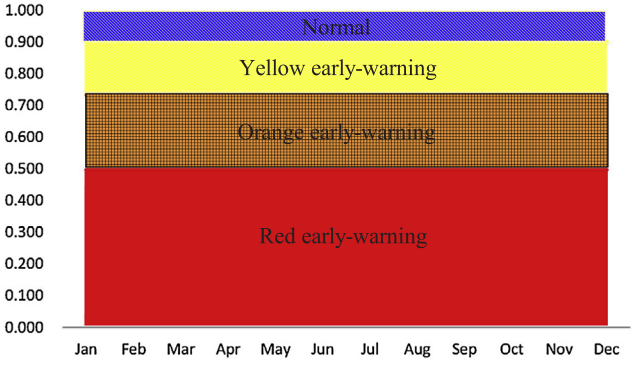
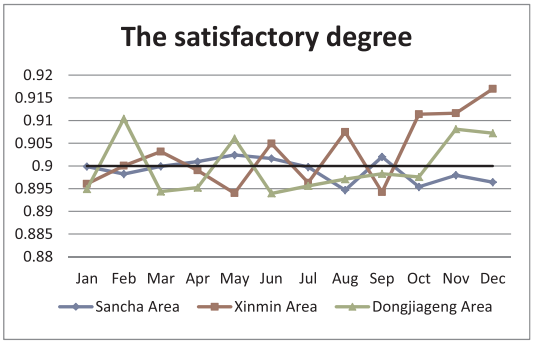


Fig. 4. Benchmark of early warning mechanism.

continues to be a major sector for most local economies, with 69% of the local economic utility derived from agricultural production, especially in the Sancha and Xinmin Areas. Because the water supply plays a key role in the development of the local agricultural sector, the Sancha Lake Area Committee usually considers the areas' situation under a moderate drought. A moderate drought results in a moderate reduction of water resource allocation to the downstream subareas, resulting in a decrease in the subareas' local economic utility and degrees of satisfaction (Table 11). From Fig. 6, it can be seen that in 80% of the months, the degree of satisfaction for the Sancha and Xinmin Areas falls into the reference interval (0.497, 0.732), and (0, 0.497) for the Dongjiageng Area reference interval. Hence, the Sancha and Xinmin Areas would issue an OEWM, and the Dongjiageng Area would issue a REWM.

The Sancha and Xinmin Areas are agriculture-intensive and use most of their water resources for irrigation. The local authority usually priorities these areas and provides them with the water they need to satisfy their net irrigation requirements. Nevertheless, widespread and continuing stress on water resources increases the risk that



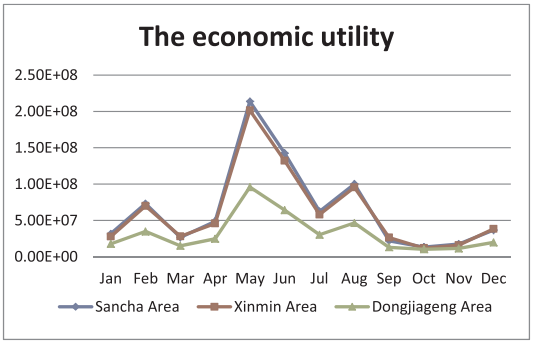


Fig. 3. The subarea objectives.

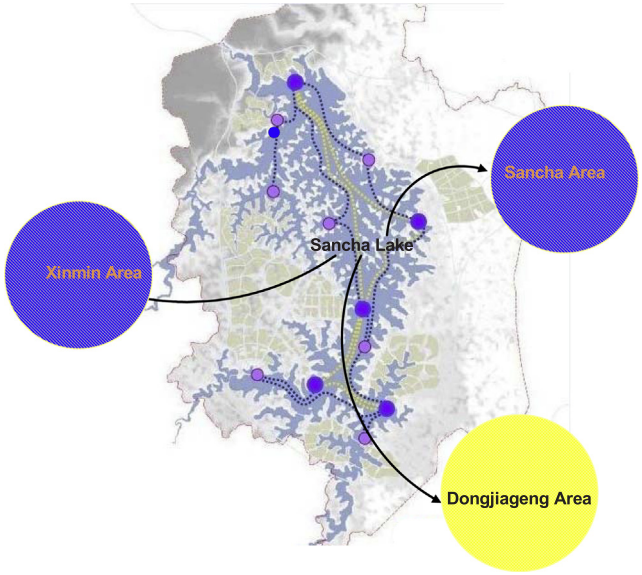


Fig. 5. Early warning figure under normal inflow level.

simultaneous water shortages might occur around the world and could even trigger a regional water crisis.

In this scenario, certain strategies need to be employed to cope with a moderate drought. To ensure agricultural production, technological intervention can be critical; for example, smaller and minor irrigation schemes with better land-use could be developed to enhance soil moisture and water retention, and even cloud seeding (induced rainfall) using solidified carbon dioxide or finely powdered sodium chloride could be a technological measure that alleviates the impact of a moderate drought. Above all, applying new and improved techniques is an efficient way to combat drought.

4.1.3. Scenario 3 – serious drought (S3)

If a serious drought occurs, it would be an extremely difficult situation for the Sancha Lake Area, with some of the worst results being regional economic downturns, food shortages, or social conflict. At an annual stream flow of less than 39.97 million m^3, the Sancha Lake Area Committee would consider this a serious situation that would result in a rapid fall in water resources allocated to downstream subareas, resulting in a decrease in the subarea's local economy utility and degrees of satisfaction (Table 12). Following Fig. 6, all subareas would issue an REWM, indicating that the degree of satisfaction in 80% of the months in the three subareas would fall into the reference interval (0, 0.497).

In this scenario, since agricultural and municipal water supplies take precedence over industrial water needs, measures can be developed to cope with a serious drought situation; groundwater would need to be used wisely, and cloud seeding would be applied as and when necessary.

4.2. Guarantee degree level

In addition, reasonable evaluation criteria would need to be developed to measure the guaranteed water supply degree level for both the Sancha Lake Area Committee and the subarea managers. For the Sancha Lake Area Committee, the guaranteed water supply degree level is defined below, to measure the extent to which available water resources can be allocated to those subareas:

$$\mathrm{SGR}^{U}(t) = \frac{A(t) + \xi(t)}{\sum_{i=1}^{m} x_i^{\mathrm{Ref}}(t)},$$

where $x_i^{\mathrm{Ref}}(t)$ is the reference value of the normal demand of subarea i in period t (Table 9).

For the manager of subarea i, the guaranteed water supply degree level is defined below, to measure the extent to which available water resources can be allocated to different production activities:

$$\mathrm{SGR}_i^{L}(t) = \frac{s_i(t) + x_i(t) + \mathrm{BSW}_i(t)}{\sum_{k=1}^{m} y_{ik}^{\mathrm{Ref}}(t)},$$

where $y_{ik}^{\mathrm{Ref}}(t)$ is the reference value of the normal demand of user k of subarea i in period t (Table 9).

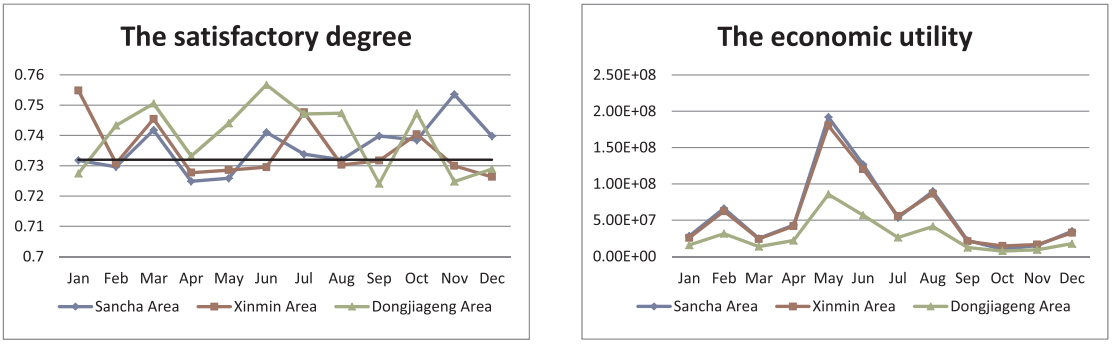
The guaranteed degree levels reflect the regulation effect of the reservoirs. The larger the guaranteed degree, the greater the capability of the Sancha Lake Basin to fight against drought. As the fluctuation of the upper reservoir is greater than the lower reservoir, the upper reservoir controls the regulatory level and the lower reservoir controls the guaranteed level (Fig. 7). Furthermore, the lower reservoir has a smaller fluctuation because the allocated upper-level water resources are used first in every period. The guaranteed degrees under the four scenarios are close, which confirms the guaranteed level of the reservoir. Therefore, the guaranteed degree can be considered an index reflecting the level of the reservoir, but it is not a suitable early-warning index, although the degree concept is more intuitive for managerial operations.

4.3. Policy implication

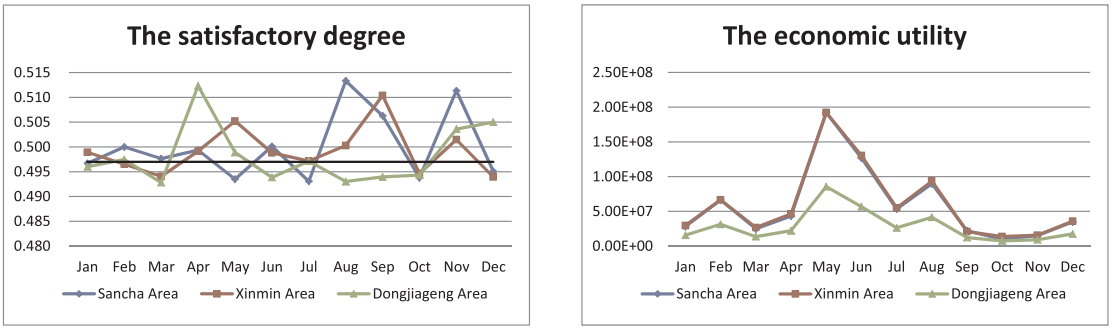
Linking Jian Yang's regional plan on "Sustainable Development Goals: Total water consumption control, water conservation and efficient use, water resource allocation, and water supply security," we aim to summarize the policy implications and underscore the roles of the bi-level stakeholders, namely the Sancha Lake Area Committee and the

Table 10
Allocation strategies for under slight drought condition (m^3).

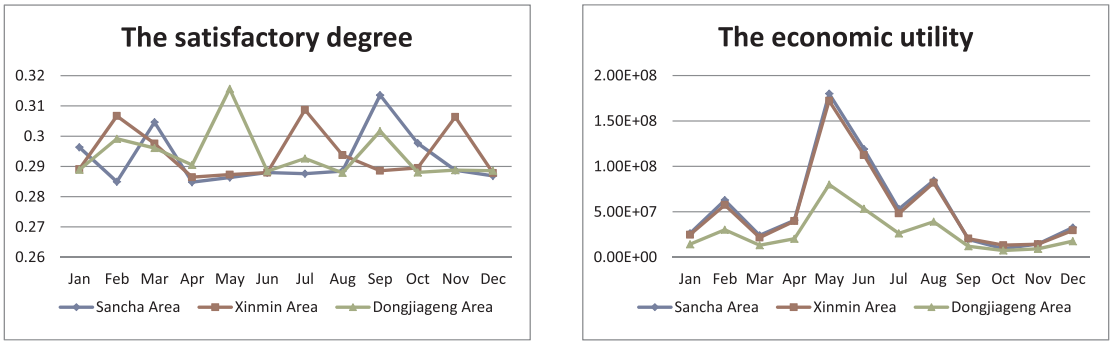
Month	SC			XM			DJG		
	$k = 1$	$k = 2$	$k = 3$	$k = 1$	$k = 2$	$k = 3$	$k = 1$	$k = 2$	$k = 3$
Jan	112.39	538.64	53.77	135.33	481.36	64.43	122.46	220.83	57.81 4
Feb	112.32	1461.38	53.79	134.79	1300.36	64.10	122.08	600.10	58.15 0
Mar	112.99	471.14	53.64	135.38	420.39	64.25	122.56	193.23	58.17 1
Apr	112.27	924.99	53.39	135.31	829.33	63.95	122.26	378.36	58.21 8
May	112.79	4506.78	53.57	134.76	4029.71	63.96	122.11	1853.13	58.31 1
Jun	112.79	2946.42	53.63	134.53	2624.91	63.98	122.41	1207.54	58.37 5
Jul	113.19	1213.31	53.54	135.36	1083.42	64.35	122.49	498.25	58.24 8
Aug	112.74	2055.16	53.50	135.59	1822.76	64.22	122.64	844.58	58.12 0
Sep	112.63	394.87	53.85	134.69	349.47	64.01	121.35	161.67	58.33 2
Oct	112.96	156.15	53.63	135.19	138.99	64.22	122.48	64.05	58.12 6
Nov	113.05	244.57	53.89	134.85	217.61	63.99	122.15	99.56	57.77 6
Dec	112.78	698.24	53.61	135.42	624.06	63.92	122.64	286.55	57.83 2



(a) Under the slight drought condition



(b) Under the moderate drought condition



(c) Under the serious drought condition

Fig. 6. The subarea objectives under different conditions.

Table 11
Subarea Allocation strategies under moderate drought condition (m^3).

Month	SC			XM			DJG		
	$k = 1$	$k = 2$	$k = 3$	$k = 1$	$k = 2$	$k = 3$	$k = 1$	$k = 2$	$k = 3$
Jan	106.20	503.87	50.12	126.00	452.69	60.22	114.95	206.31	54.62
Feb	105.74	1371.23	50.33	126.05	1229.03	60.34	113.93	562.09	54.61
Mar	106.18	439.73	50.54	126.09	394.06	59.92	115.07	179.75	54.50
Apr	105.41	866.72	50.55	126.74	773.94	60.48	114.48	356.01	54.27
May	105.82	4225.69	50.21	126.67	3765.22	60.28	114.70	1734.94	54.53
Jun	105.92	2760.34	50.17	125.92	2449.14	60.49	115.08	1123.61	54.34
Jul	105.20	1138.33	50.38	127.19	1011.01	60.14	114.15	465.41	54.24
Aug	105.90	1929.67	50.42	126.90	1706.82	60.21	114.32	792.91	54.29
Sep	105.59	370.45	50.29	126.91	330.49	59.94	114.38	151.55	54.71
Oct	105.22	146.68	50.17	125.94	130.20	60.02	114.77	60.00	54.20
Nov	105.75	228.91	50.60	127.09	203.10	60.35	114.84	94.07	54.31
Dec	105.39	655.24	50.10	127.19	582.20	60.13	113.91	267.08	54.19

Table 12
Subarea Allocation strategies under serious drought condition (m^3).

Month	SC			XM			DJG		
	$k = 1$	$k = 2$	$k = 3$	$k = 1$	$k = 2$	$k = 3$	$k = 1$	$k = 2$	$k = 3$
Jan	99.44	474.99	47.27	119.37	425.62	56.42	107.50	194.20	51.01
Feb	98.93	1287.48	47.25	119.17	1155.91	56.78	107.50	530.65	51.43
Mar	99.99	415.46	47.51	118.94	370.64	56.57	107.91	169.96	51.12
Apr	99.15	821.03	47.09	118.46	724.17	56.79	107.80	333.49	51.31
May	99.02	4003.30	47.11	119.50	3537.53	56.86	108.05	1641.12	51.54
Jun	99.28	2580.45	47.46	118.86	2295.68	56.74	107.50	1056.05	51.21
Jul	99.46	1068.32	47.43	119.25	958.73	56.85	107.29	438.29	51.37
Aug	99.03	1821.01	47.38	119.44	1623.31	56.50	107.13	740.29	51.41
Sep	100.11	349.51	47.50	118.52	310.11	56.85	108.03	142.37	51.21
Oct	99.31	138.07	47.49	118.55	122.24	57.01	107.29	56.20	51.35
Nov	99.27	214.29	47.53	119.16	192.06	56.94	107.53	88.00	51.01
Dec	98.99	619.37	47.24	119.07	546.27	56.40	107.74	251.24	51.52

subarea managers.

Proposition 1. *The government establishes an emergency response cooperative mechanism for each subarea.*

According to the simulation results under the various climate change scenarios, an emergency response cooperative mechanism can be constructed by the comparative analysis of objective functions under different scenarios (as seen in Tables 13,14). Fig. 8 shows the different early-warning mechanisms under varying annual stream inflow scenarios.

The Dujiangyan Longquanshan irrigation district is devoted to building an intelligent water management system by combining technology modernization and sustainable development. The 4-level early-warning mechanism for drought scenarios in this river basin has been successfully designed. The macro-control policy has been formulated for the irrigation areas, industrial usage, and dynamic residential water usage strategies.

When it comes to implementation, different strategies need to be employed to cope with slight, moderate, and serious droughts. Under the slight drought condition, the Sancha Lake Area Committee could design a reasonable coordination mechanism to improve water resource transactions. For example, financial subsidies can be paid to the subareas with a minimum satisfaction level, or unaffected areas could be encouraged to transfer some water rights to the OEWM subarea. Under the moderate drought condition, technological interventions should be adopted that are an efficient way to combat drought. Under the serious drought situation, other types of water resources can be taken into consideration (e.g. groundwater, virtual water), in addition to improving the irrigation technology.

Proposition 2. *The Sancha lake area committee should consider apply for special, permanent water rights coping with increasing water demand*

Proposition 3. *The Sancha Lake Area Committee should consider applying for special, permanent water rights to cope with increasing water demand*

Since China became a member of the WTO, the Sancha Lake Area has rapidly developed, increasing its water use demands. To save water, and to reduce the chance of water shortages, a stepped water price mechanism for different industrial uses was suggested, but neither the Sancha Lake Area Committee nor the Dujiangyan Administration Bureau had the right of revision. Therefore, to lessen the impact of water shortages resulting from the increase in demand from the recent

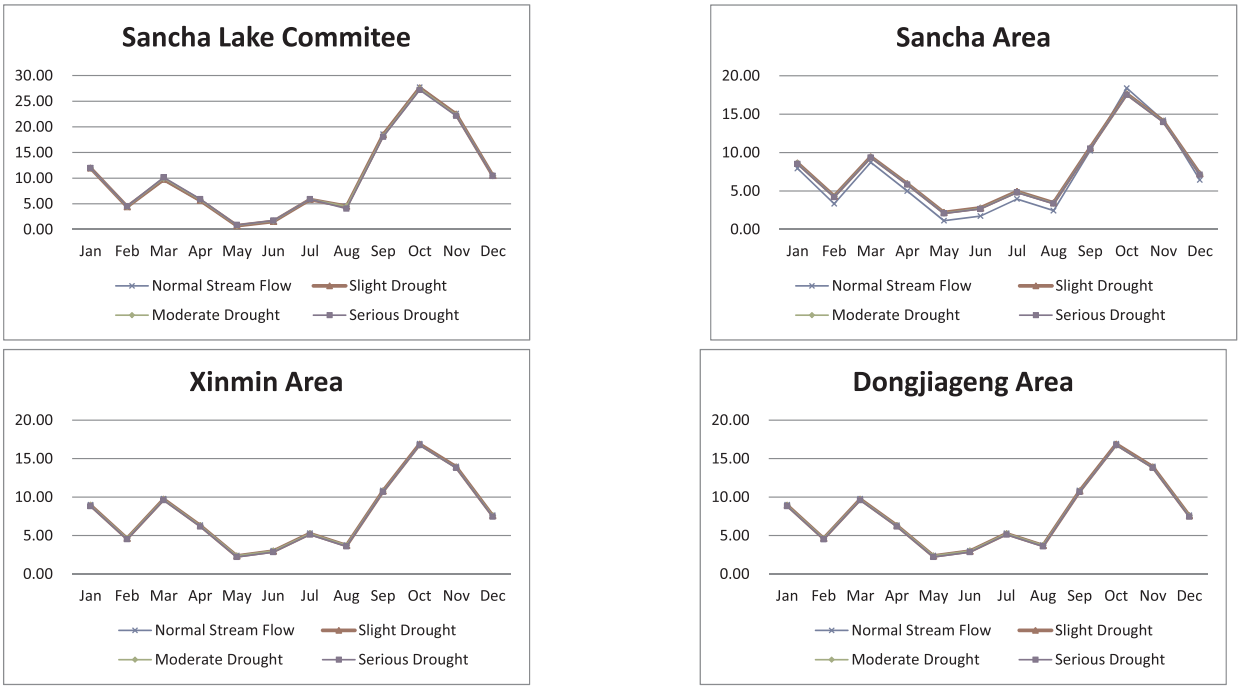


Fig. 7. Sancha Lake area committee and subarea water manager guarantee degrees under different scenarios.

Table 13
The satisfaction degree of each subarea under various scenarios.

Area	Obj	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SC	*Normal*	0.900	0.898	0.900	0.901	0.902	0.902	0.900	0.895	0.902	0.895	0.898	0.896
	Slight drought	0.732	0.730	0.742	0.725	0.726	0.741	0.734	0.732	0.740	0.738	0.754	0.740
	Moderate drought	0.497	0.500	0.498	0.499	0.493	0.500	0.493	0.513	0.506	0.494	0.511	0.495
	Serious drought	0.296	0.285	0.305	0.285	0.286	0.288	0.288	0.288	0.314	0.298	0.289	0.287
XM	*Normal*	0.896	0.900	0.903	0.899	0.894	0.905	0.896	0.907	0.894	0.911	0.912	0.917
	Slight drought	0.755	0.731	0.745	0.728	0.729	0.730	0.748	0.730	0.732	0.740	0.730	0.726
	Moderate drought	0.499	0.497	0.494	0.499	0.505	0.499	0.497	0.500	0.510	0.495	0.501	0.494
	Serious drought	0.289	0.307	0.298	0.286	0.287	0.288	0.309	0.294	0.289	0.290	0.306	0.288
DJG	*Normal*	0.895	0.910	0.894	0.895	0.906	0.894	0.896	0.897	0.898	0.898	0.908	0.907
	Slight drought	0.727	0.743	0.751	0.733	0.744	0.757	0.747	0.747	0.724	0.747	0.725	0.729
	Moderate drought	0.496	0.497	0.493	0.512	0.499	0.494	0.497	0.493	0.494	0.494	0.504	0.505
	Serious drought	0.289	0.299	0.296	0.290	0.316	0.288	0.293	0.288	0.302	0.288	0.289	0.289

Table 14
The economic utility of each subarea under various scenarios (10^8 RMB).

Area	Obj	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SC	*Normal*	0.316	0.731	0.266	0.488	2.138	1.424	0.624	1.002	0.219	0.133	0.175	0.367
	Slight drought	0.282	0.697	0.257	0.453	2.052	1.347	0.597	0.946	0.238	0.113	0.162	0.361
	Moderate drought	0.281	0.663	0.249	0.433	1.920	1.268	0.535	0.898	0.221	0.099	0.150	0.347
	Serious drought	0.263	0.628	0.241	0.407	1.800	1.190	0.531	0.845	0.197	0.094	0.145	0.326
XM	*Normal*	0.278	0.700	0.280	0.458	2.014	1.320	0.580	0.955	0.265	0.120	0.160	0.382
	Slight drought	0.296	0.666	0.269	0.463	1.924	1.304	0.550	0.935	0.210	0.137	0.157	0.359
	Moderate drought	0.296	0.666	0.269	0.463	1.924	1.304	0.550	0.935	0.210	0.137	0.157	0.359
	Serious drought	0.247	0.575	0.217	0.398	1.722	1.124	0.481	0.819	0.204	0.133	0.143	0.296
DJG	*Normal*	0.177	0.349	0.150	0.248	0.959	0.642	0.303	0.465	0.130	0.103	0.115	0.198
	Slight drought	0.162	0.339	0.144	0.228	0.915	0.602	0.298	0.438	0.140	0.090	0.113	0.187
	Moderate drought	0.157	0.314	0.136	0.221	0.856	0.568	0.262	0.414	0.123	0.075	0.092	0.176
	Serious drought	0.143	0.303	0.132	0.203	0.800	0.533	0.263	0.391	0.120	0.074	0.092	0.177

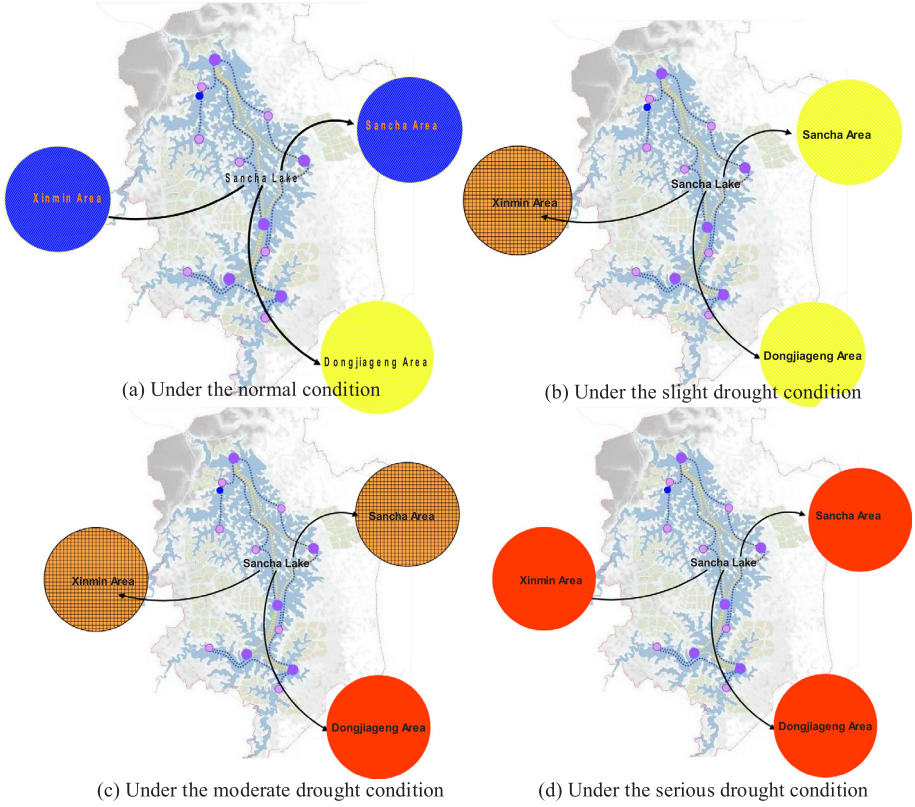


Fig. 8. Early warning figure under various stream inflow level.

implementation of the "Tianfu New" plan, the Sancha Lake Area Committee was required to apply for special permanently increased water rights, rather than applying for temporary water rights every year at the hearing for the new Dujiangyan Irrigation System water resources allocation plan at the beginning of the 13th Five-Year Plan (2015–2020). In preparation for this hearing, the Dujiangyan Administration Bureau called on all committees to submit their water resource allocation requirements. As a benchmark for the Sancha Lake Area Committee water resource allocation plan, a set of integrated alternatives were discussed along with the water rights application handed out by the Dujiangyan Administration Bureau to other areas as planning guidelines, which included the following operating schedule strategies:

(1) The committee controls the water rights, unifies the water resource allocation operating schedule, and executes the prescribed management needs, which would allow the subareas to distribute water for municipal, industrial, and agricultural uses.
(2) The committee guarantees the use of water for irrigation, residential, and industrial use, while also paying attention to ecological and wider/varied water usage needs.
(3) The committee draws up a water usage contract with the subareas that outlines the charges and fees for water use. Water trading between subareas is encouraged, but supervised by the committee.

Proposition 4. *The subarea managers should consider water quota transactions and water saving and water usage efficiency improvements*

The subareas are required to do business under a fixed total water quota and are also required to save water wherever possible. The productive use of water should be improved by a rational application of technology and economics, and by logical decision-making. For industrial and municipal water use, water use efficiency can be improved through technological innovations, new policies, and simple operational improvements. For agricultural water use, efficient irrigation technologies need to be employed to boost food production while working with a limited water supply. For example, precision irrigation, soil moisture monitoring, and the laser leveling of fields have the potential to double the output per unit of water for many crops.

4.4. Findings and feedbacks

The bi-level dynamic equilibrium decision-based water resources allocation model has been employed in three subareas, made up of a total of 41 towns and villages, in the Sancha Lake area during 2011–2012. The Committee allocated water rights optimally for around 6,687 hectares of irrigation, more than 50 key enterprises, and a population of almost 56,000 people, achieving a sustainable utilization of water resources in the Dujiangyan Longquanshan irrigation district. With strong practicability, operability, and a wide range of applications, the model for water resources allocation can be applied to each subarea of the Dujiangyan Longquanshan irrigation district. This research applied a qualitative technique: a team of eight water governance officials and scholars gathered to describe their findings and give feedback after a real-world practice process that was collaboratively designed and executed. All members participated in regular meetings to discuss the results of the water allocation strategy solved by the proposed model, and they gathered the following points.

1: the mechanism of dynamic water rights trading can overcome the difficulty of uneven annual inflows

The Committee controlled the water rights, unified the operations schedule for the water resources allocation, and executed the prescribed management systems that allowed the subareas themselves to distribute the water for municipal, industrial, and agricultural uses in the Sancha Lake area. Based on the macro-control of upstream flow by the Administration Bureau of the Dujiangyan Longquanshan Irrigation District, the Committee overcame the difficulty of uneven annual inflows, dominated the dynamic trading of water rights, optimized the equilibrium allocation of water resources, and balanced the water supply in the Sancha Lake area.

2: quota management is effective in the Sancha irrigation area

The Committee adopted policies that allocated water volumes to subareas in the Sancha Lake area under fixed total volume and controlled through quota management. The subareas were required to make a contract with the Committee, and were charged strict fees according to the contract. The Committee first guaranteed residential water use, promoted agricultural water-saving irrigation techniques, and identified water-saving requirements for the production value of increased industrial water use while paying attention to both ecological and various other water uses. Naturally, they are also fully committed to the sustainable allocation of water resources in the Sancha Lake area.

5. Conclusions

The significant stress caused by unsustainable water resource allocation has been a perplexing problem for Sancha Lake, an important area in the southeast basin of the Dujiangyan Irrigation System in China. Because of the possibility of unpredictable water availability in the Min River Basin, a multi-objective multi-stage Stackelberg-Nash-Cournot model was proposed to allocate water resources optimally, on the basis of water rights distribution. The goals of the upper-level authority, the Sancha Lake Area committee, were to optimize the total social degrees of satisfaction and water availability levels. The goals of the three lower-level subareas were the degrees of satisfaction for the available water resources and economic benefits. Compared to previous studies, this multi-objective multi-stage decision making process considered bi-level optimization, and two types of state transit equations were established for the upper and lower levels in order to optimize their water resource planning dynamically. To solve the complex and nonlinear bi-level multi-objective multi-stage decision making model, a policy simulation system with an IDP-GA was designed to create the optimum allocation of water resources under various climate scenarios. Finally, the results under four climate change scenarios were presented to demonstrate how efficient water resources allocation could be prescribed.

The proposed model was applied to optimally allocate water resources and evaluate the effects of several climate scenarios in a river basin in China, the Dujiangyan basin. First, under normal stream inflows, some important insights were obtained: (1) The m^2SNC model is an efficient tool for tackling this type of problem in complex situations, and it provides an efficient allocation mechanism to dynamically cope with potential water crises. (2) The subareas were able to develop real-time storage-production strategies based on the water rights they obtained and available water as regulated by the authority. (3) Irrigation and municipal water were guaranteed, as the upper authority gave priority to areas with major agricultural production and larger populations.

Second, according to the simulation results under the various climate change scenarios, we can suggest several policy implications for the decision process. For example, an emergency response cooperative mechanism should be established by the government for each subarea, and the Sancha Lake Area Committee should consider applying for special, permanent water rights to cope with increasing water demand. To increase its credibility, a group of government officials and scholars were called together to analyze the results of the proposed model in the Sancha Lake area, which confirmed that the mechanism of dynamic trading of water rights can overcome the difficulty of uneven annual inflows, and that quota management is effective in the Sancha irrigation area.

According to the Third Plenary Session of the 18th Central Committee of the Chinese Communist Party, it is the government's responsibility to develop a complete market mechanism, and to formulate policies to promote and support the reformation of water rights

allocation. The proposed model can be extended to the world marketplace, including developing nations. Other, more complicated situations, such as the cat and mouse game played out between lower-level decision makers and other uncertain factors integrated on the upper level, still need to be modeled to determine the optimum water allocation for realistic problems. From a policymaking perspective, a reasonable pricing strategy and a transactional code of conduct are provided. In the future, policymaking support can be systematically simulated to cope with every conceivable scenario.

Appendix A. Appendix I: Pseudo Code

Algorithm 1: IDP-GA

Input: GA parameters
Output: Best solution
1. $t \leftarrow 0$
2. initialize $P^U(t)$ \\$P^U(t)$: population of chromosomes
3. **while** not termination condition
4. $C^U(t) \leftarrow P^U(t)$
5. **function** LowerGA$P^U(t)$;
6. **return** $P_*^L(t)$ \\$P_*^L(t)$:the best chromosomes of lower-level
7. **end function**
8. fitness eval($P^U(t)$, $P_*^L(t)$);
9. select $P^U(t+1)$ from $C^U(t)$; \\$P^U(t+1)$: offspring
10. crossover $P^U(t)$ to yield $P^U(t+1)$;
11. mutation $P^U(t)$ to yield $P^U(t+1)$;
12. $t \leftarrow t+1$;
13. **end while**
14. **return** best solution $Y(P_*^U, P_*^L)$; \\ Return the best solution of IDP-GA

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